New method based on energy- and particle-flow in $e^+e^- \to W^+W^- \to hadrons$ events for colour reconnection studies

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LAPP-EXP 2000-02
April 2000

NEW METHOD BASED ON ENERGY- AND PARTICLE-FLOW IN $e^+e^- \rightarrow W^+W^- \rightarrow$hadrons EVENTS FOR COLOUR RECONNECTION STUDIES

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abstract

A method to study colour reconnection effects in hadronic decays of W pairs produced in e^+e^- annihilation is described. It is based on the study of the particle and energy flow between jets associated to the same W boson and between two different W bosons in four quark events. The interjet activity shows interesting sensitivity to hadronisation models incorporating colour reconnection schemes. This method seems quite promising for future colour reconnection studies to be performed at LEP.

This work was presented at the Workshop on WW Physics at LEP200
Kolymbari-Chania (Greece), 20-23 October 1999

1 Intoduction

In the process $e^+e^- \to W^+W^- \to hadrons$ it has been suggested that interactions may occur between the decay products of the two W bosons [1–4]. As a result the colour flow pattern of these events are modified. Colour rearrangement between two colour singlets are expected from simple QCD principles.

The W bosons produced in e^+e^- annihilation decay at short distances (≈ 0.1 fm). Consequently, the hadronisation of the two quark pairs occurs with a large space-time overlap, since the typical hadronic scale is about 1 fm. Colour reconnection (CR) effects are thought to be suppressed in the hard perturbative phase, but may have larger effects in the non-perturbative stage of the hadronisation process [2]. While hard gluons ($E_g > \Gamma_W$) are emitted incoherently by the two original colour singlets only soft gluons could in principle feel the collective action of both systems and thus participate in cross-talks. The net effect should appear in inclusive soft particle distributions as a change of the mean particle multiplicity as well as a change in momentum spectra.

In the absence of any cross-talk one can imagine 2 strings being stretched between the two quarks from the two W bosons as shown in figure 1a). Subsequently these 2 strings fragment to produce the hadrons which can be uniquely assigned to a W boson. In case of

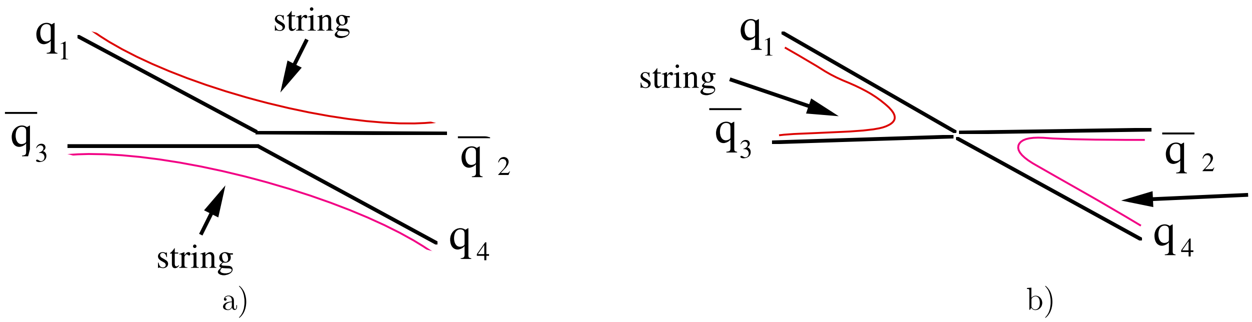

Figure 1: Coloured string topology in W$^+$W$^-$ $\to q_1\bar{q}_2\bar{q}_3q_4$ for a) no cross talk and b) immediate reconnection scenario.

colour reconnection the modifications of this simple string topology picture would result in some depletion and/or enhancement of soft particles in specific phase space regions, especially between the jets. Figure 1b) shows an other topology where the strings are stretched between quarks of different W bosons. It corresponds to the immediate reconnection scenario [1] which is very unlikely to happen but gives the strongest effect on the interjet particle activity.

In this paper I introduce a new method based on the study of the energy flow and particle flow distributions in 4-jet events to search for effects of particle depletion and enhancement in a model independent way. [1] The analysis is developped using Monte-Carlo event samples at e^+e^- centre-of-mass energy equal to 189 GeV

2 Event selection

In e$^+$e$^-$ $\to$ W$^+$W$^-$ $\to$ hadrons process, events are characterised by large particle multiplicity and good energy balance. The selected events should have 4 jets reconstructed with the Durham algorithm with $y_{cut} = 0.01$.

[1] It should be noted that this method was presented by the author in a plenary talk given at the Workshop on WW Physics at LEP200 which was held in Kolymbari-Chania (Greece) during October 1999

For the study of the particle- and energy flow between jets, the initial quark configuration should be well reconstructed with a nearly perfect quark-jet association. At 189 GeV, the W bosons produced in e^+e^- annihilation have a non negligible boost and this property is used to select unambiguous topologies in a sample of 4-jet events. This selection is made in such a way as to select topologies corresponding to Figure 1a), and to prevent the selection of events where the two strings cross each other and for which the cross-talk effects cannot be easily traced.

The criteria correspond to cuts on the four interjet angles. The two largest interjet angles should be between 100° and 140° and not adjacent. The two other interjet angles should be less than 100°. This selection guarantees similar sharing of energy between the four primary partons with the two strings evolving back to back. These cuts have been chosen by studying carefully the Monte Carlo $\mathrm{W^+W^-}$ events.

Applying all the cuts the final sample at 189 GeV gives an efficiency of 15% for $\mathrm{e^+e^-} \rightarrow \mathrm{W^+W^-} \rightarrow \mathrm{q\,\bar{q}q\,\bar{q}}$. The probability to have the right pairing (i.e. the topology of fig. 1) is estimated to be 87%.

3 Flow distributions

We start by defining the plane spanned by the most energetic jet (jet 1) and the jet associated to the same W (jet 2) (Figure 2). For each event we project the direction of all the particles onto this plane. The energy and particle flows are measured as a function of the angle on the plane between the jet 1 and the projected momentum vector. This angle is defined as increasing from jet 1 toward jet 2 (from same W), then to the closest jet from the other W (jet 3) toward the remaining jet (jet 4) and back to jet 1. A particle i making an angle ϕ_i with respect to jet 1 adds an entry equal to 1 in the particle flow and adds an entry equal to its energy in the energy flow for the corresponding ϕ bin.

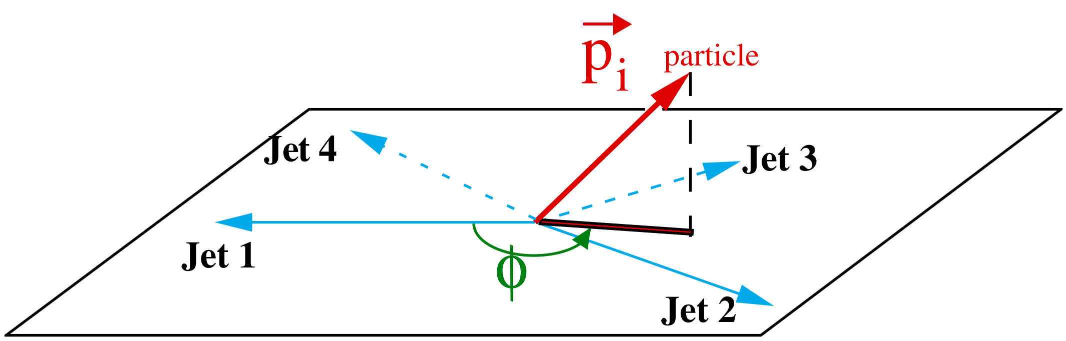

Figure 2: Illustration of the method used to build the flow distributions

The distributions are calculated for three different particle definitions:

- All stable particles of more than 100 MeV
- The charged particles with momentum $p > 100$ MeV
- The charged particles with momentum p such that $0.1 \text{ GeV} < p < 1$ GeV

The particle flow distribution obtained with all particles is shown in Figure 3(left) for the KORALW Monte Carlo [5] prediction for $\mathrm{q\,\bar{q}\,q\,\bar{q}}$ events. Figure 3(right) shows the energy flow obtained with the particles. The contribution of each event to the energy flow is normalised to the total event energy.

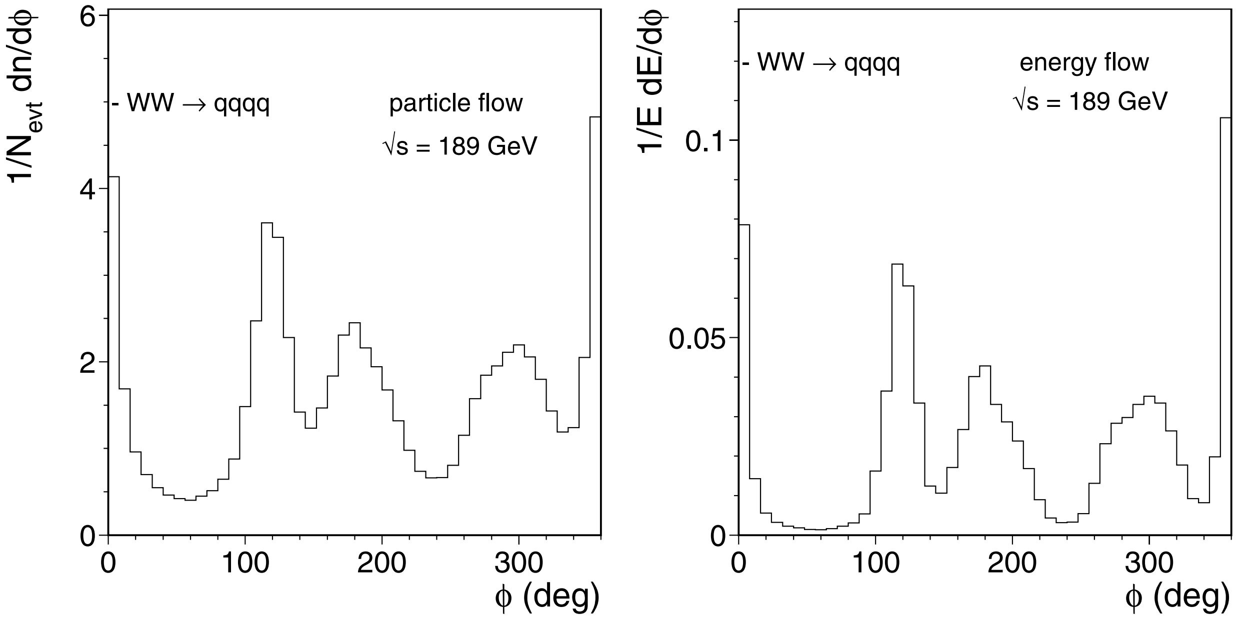

Figure 3: Particle and energy flow distributions obtained with particles at $\sqrt{s} = 189$ GeV for standard KORALW Monte Carlo prediction.

The 4-jet structure is clearly visible with the decay products of one W covering the region starting from 0 to ≈ 120 degrees while the second W covers the angular region from 140 to 340 degrees.

Having one jet as a reference for all particles makes the direct comparison of the jet1-jet2 particle activity with the jet3-jet4 particle activity difficult. In order to compare the interjet regions the angles on the plane are redefined using a rescaling procedure making use of the relative angle of the particle with the two closest jets. For a particle i located between jets j and k, the rescaled angle is: $\phi_i^{resc} = \phi_i/\phi_{jk}$ where ϕ_{jk} is the angle between jets j and k. With this definition the four jets have fixed rescaled angle values equal to 0, 1, 2 and 3.

A second transformation is performed in order to take into account the fact that the W events are not planar. Figure 4 shows the angle α between the two W decay planes defined by the (jet1-jet2) plane and the (jet3-jet4) plane. The angle is clearly not peaked at zero like it should be for planar events.

This transformation consists of using four planes for projecting the particles instead of only one. The four planes correspond to the planes spanned by each pair of adjacent jets. The particles located between two jets are then projected only on the plane spanned by these two jets. Thus the colour pattern existing between the two partons can be studied.

Figure 5 (left) shows the rescaled normalised particle flow. The line corresponds to the standard KORALW prediction for $\mathrm{q\bar{q}q\bar{q}}$ events without CR. The distribution obtained with particles of momentum less than 1 GeV is shown in Figure 5 (right). It should be noticed that the choice of four planes helps in symmetrising the flow distributions: the interjet activity in the regions corresponding to the two W "strings" in the Monte Carlo are now identical as expected. (This was not the case before this procedure). In the presence of cross-talk between W's, such a symmetry may be broken.

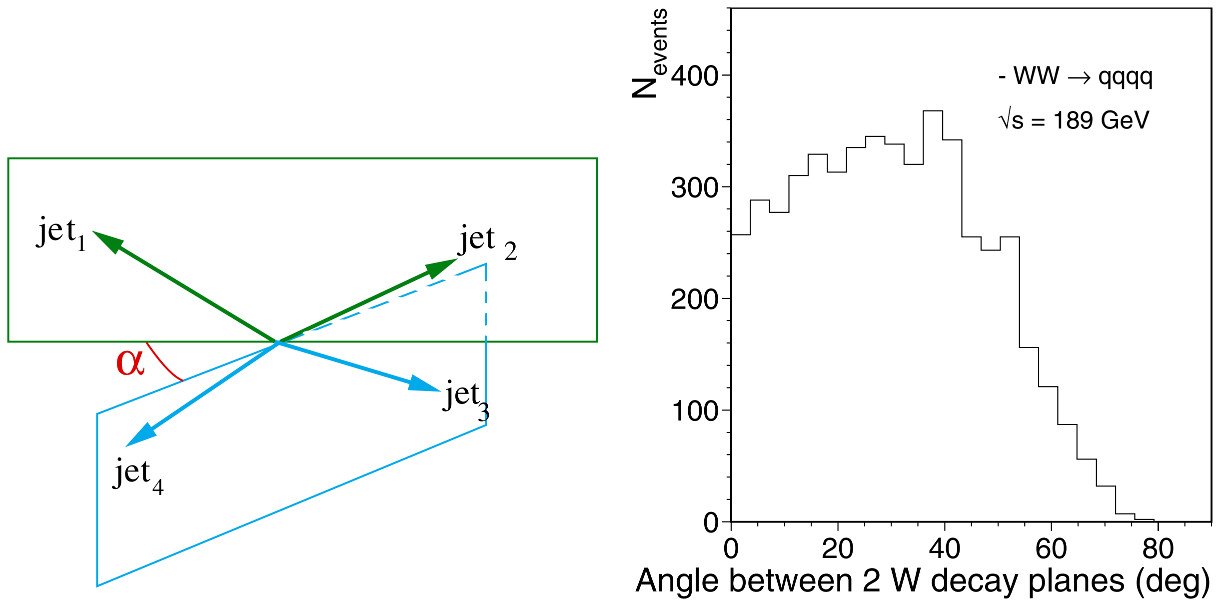

Figure 4: Distribution of the angle between the 2 reconstructed W decay planes at $\sqrt{s} = 189$ GeV.

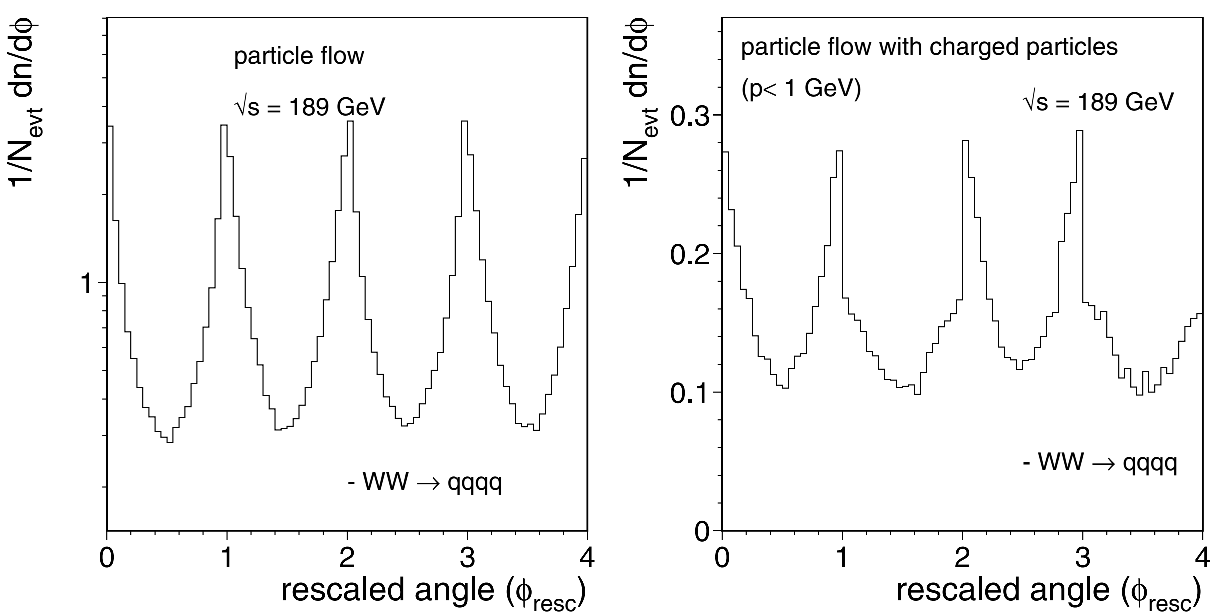

Figure 5: Particle flow distributions as a function of the rescaled angle for KORALW prediction at $\sqrt{s} = 189$ GeV.

4 Model predictions

The study is performed with various CR models which are implemented in the PYTHIA6.1 Monte Carlo program [6].

The models SKI and SKII [2] are based on the analogy between coloured strings and superconductors of type I or II with either a finite transverse size or with no lateral extent. The reconnection occurs at the crossing of the two string entities (elongated bags or vortex lines).

The GH model is a simplified implementation in PYTHIA of the model described in reference [3] where the reconnection is allowed only if it reduces the string length. The reconnection probability in this implementation is 92% as compared to 34% and 32% in the SKI and SKII models respectively.

Colour reconnection effects could appear as depletion or enhancement of particles between the quark jets. Figure 6 (top) shows the particle flow distributions obtained with the PYTHIA Monte Carlo at particle level for particles having a momentum greater than 100 MeV. The full line corresponds to no colour reconnection while the dashed line corresponds to the prediction from the GH model implemented in PYTHIA. The interjet regions corresponding to the two W bosons are named A and B while the interjet regions between two jets from different W are named C and D as indicated on the plot. We observe that the GH model gives some depletion in the regions A and B and some enhancement of particle rates in the regions C and D, as expected.

For flow distributions computed as a function of the rescaled angle the regions A and B, as well as the regions C and D, can be averaged in order to reduce the statistical uncertainty. The averaged results are shown in the two bottom plots of Figure 6.

The ratio of the particle activity between the quarks from the same W (regions A+B) and the particle activity between quarks from a different W (regions C+D) is found to be a sensitive observable to the cross-talk effects. This ratio computed from the particle flow distributions at particle level as a function of the rescaled angle is shown in Figure 7. The full line corresponds to the PYTHIA prediction without CR, the dashed line is the prediction from the SK I scenario and the dotted line corresponds to the prediction of the GH model. Figure 8 shows the distributions of the ratio of the energy flows built with particles having a momentum less than 1 GeV.

The differences between the models with and without reconnection schemes are larger in the middle of the interjet regions.

Therefore in order to quantify the colour reconnection effects the ratio R is computed in a restricted ϕ_{resc} interval ranging from 0.3 to 0.7. The corresponding variables for particle (R_N) and energy flow (R_E) are defined like:

$$R_N = \frac{\int_{0.3}^{0.7} \frac{1}{N} \cdot \frac{dn}{d\phi}(regions A+B)}{\int_{0.3}^{0.7} \frac{1}{N} \cdot \frac{dn}{d\phi}(regions C+D)} \quad \text{and} \quad R_E = \frac{\int_{0.3}^{0.7} \frac{1}{E} \cdot \frac{dE}{d\phi}(regions A+B)}{\int_{0.3}^{0.7} \frac{1}{E} \cdot \frac{dE}{d\phi}(regions C+D)}$$

The values obtained for R_N using all particles at particle level are given in table 1 for the model without CR and for the SKII, SKI and GH models. The errors quoted are coming from Monte Carlo statistics only.

The SK models show effects of the order of about 4% with these variables while the GH model implemented in PYTHIA (having a high reconnection probability) shows a larger effect of about 10%.

On a purely statistical basis one can see that at the end of the LEP2 program with improved analysis the statistical precision of a single experiment could reach a level of 0.02. We can then

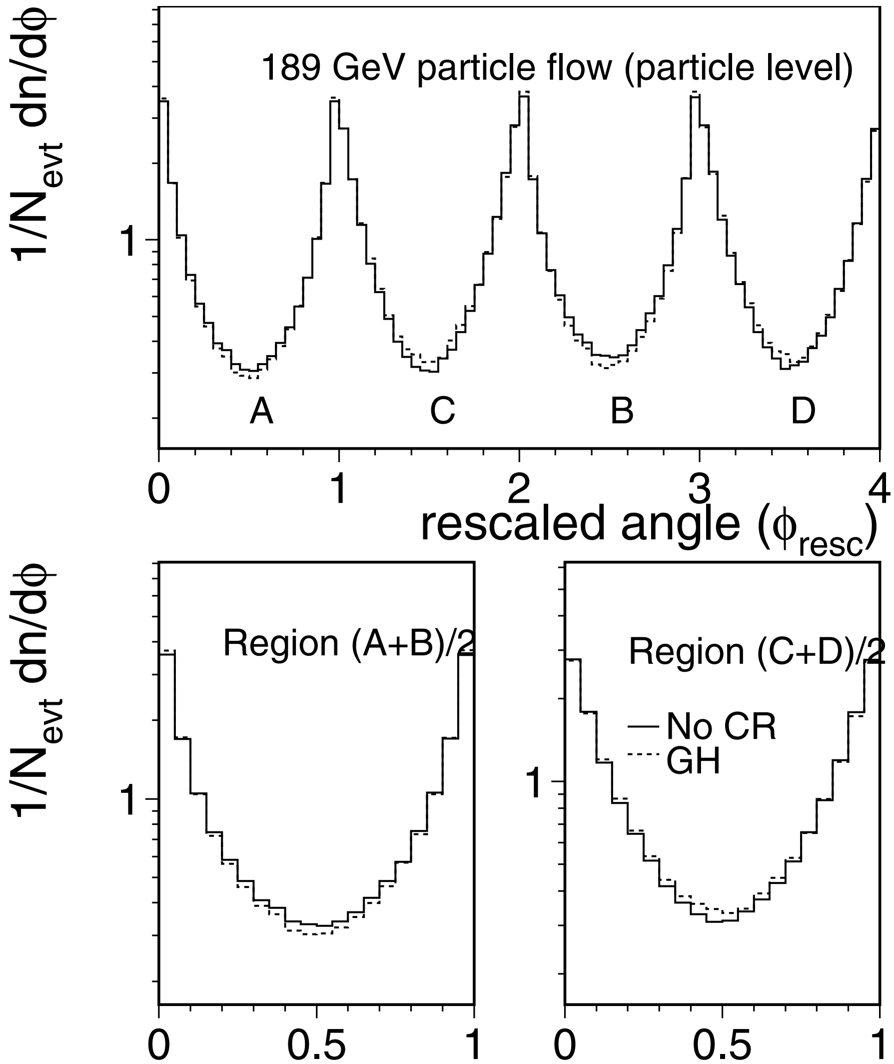

Figure 6: PYTHIA prediction at $\sqrt{s} = 189$ GeV for the particle flow distribution at particle level without colour reconnection (No CR) and for the GH model.

Model	R_N particle
No CR	1.004 ± 0.006
SkII	0.977 ± 0.006
SKI	0.974 ± 0.006
GH	0.898 ± 0.006

Table 1: Values of R_N at particle level

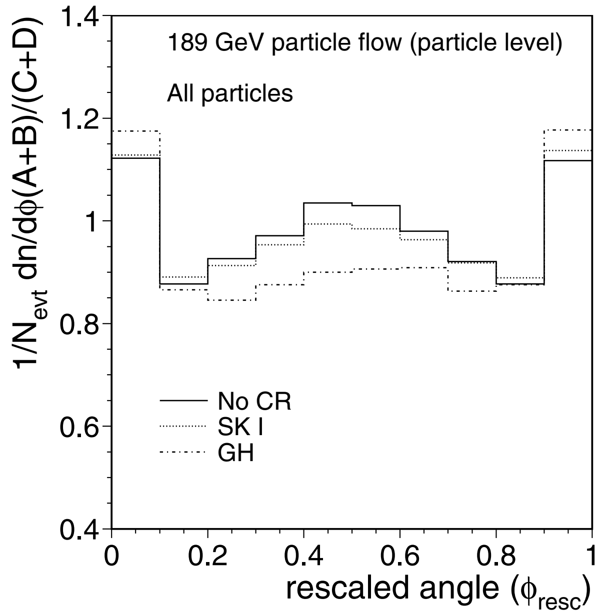

Figure 7: Ratio (R) of the particle flow in regions (A+B) divided by the particle flow in regions (C+D) at particle level.

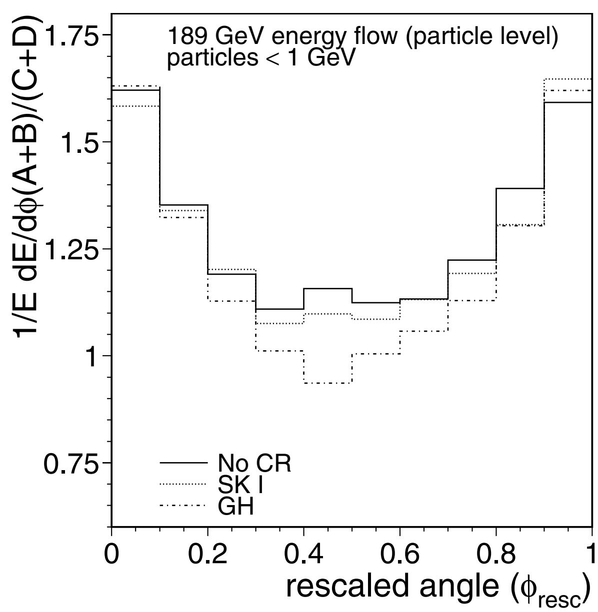

Figure 8: Ratio (R) of the energy flow in regions (A+B) divided by the energy flow in regions (C+D) at particle level for particles having a momentum less than 1 GeV.

Model	R_E particle
No CR	1.131 ± 0.014
SkII	1.117 ± 0.014
SKI	1.098 ± 0.014
GH	1.002 ± 0.015

Table 2: Values of R_E at particle level

expect to be significantly sensitive to effects at the 10% level and to be able to probe models like the GH one.

The same conclusions are obtained when looking at the table 2 which shows the R_E values computed from charged particles at particle level having a momentum less than 1 GeV.

5 Asymmetry variables

When developping this analysis an other set of variables, showing more sensitivity, have been found. They correspond to asymmetry in particle and energy population between jets. These quantities are computed starting from the energy and particle flow for each event. It is equivalent to computing the difference of the activity between jets from the same W with the activity between jets from different W event by event. The same angular range (0.3 to 0.7) is considered in each region.

The asymmetry in energy (A_E) and in particle density (A_N) are defined by:

$$A_E = \frac{E_A+E_B-E_C-E_D}{E_A+E_B+E_C+E_D} \text{ and } A_N = \frac{N_A+N_B-N_C-N_D}{N_A+N_B+N_C+N_D}$$

where the subscripts A, B, C and D correspond to the interjet regions defined previously. For each region i:

$$N_i = \int_{0.3}^{0.7} \frac{dN}{d\phi} d\phi \ ; \qquad E_i = \int_{0.3}^{0.7} \frac{dE}{d\phi} d\phi$$

The distributions of A_E obtained with all particles are shown in figure 9 at particle level. The models shown are the one without CR effect (No CR) and the SKI and GH models. The effect of particle enhancement in the regions between jets from different W bosons is visible as a shift of the distributions towards negative asymmetry.

The corresponding distributions of A_N are shown in figure 10 where the trend is similar. The difference with A_E comes essentially from the absence of energy weighting for each particle.

The effects can be quantified by measuring the mean values of the distributions for the various models. Table 3 summarises the results for $< A_N >$ and $< A_E >$ obtained with the models without CR and SKII, SKI and GH models. These mean values show better sensitivity to the CR effects compared to the R variable. The SKII, SKI and GH models show effects of the order of 10%, 20% and more than 50% respectively. This starts to be interesting compared to the estimated precision that should be reached at the end of LEP2.

An other interesting quantity is the angle between a particle and the direction of the bisector between two jets. This angle is sensitive to the presence of rapidity gaps. It should increase

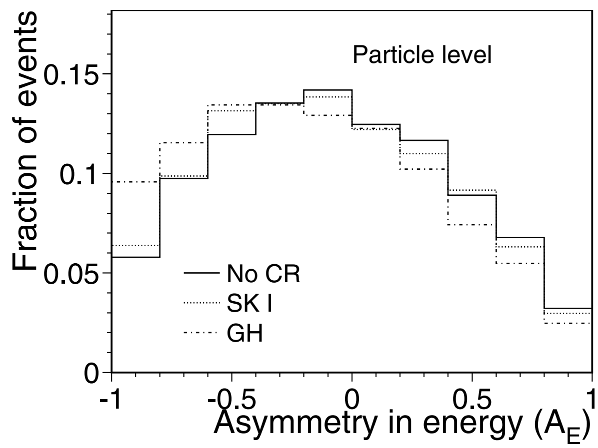

Figure 9: Distributions of the energy asymmetry at particle level for various models

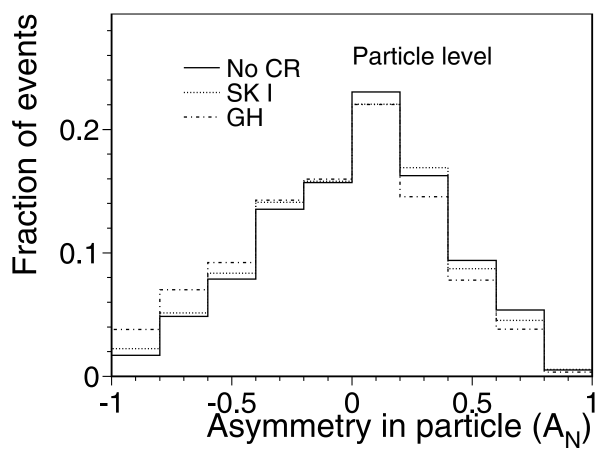

Figure 10: Distributions of the particle multiplicity asymmetry at particle level for various models

particle level		
Model	$< A_E >$	$< A_N >$
No CR	-0.069 ± 0.005	-0.005 ± 0.004
SkII	-0.088 ± 0.005	-0.020 ± 0.004
SKI	-0.088 ± 0.005	-0.025 ± 0.004
GH	-0.153 ± 0.005	-0.075 ± 0.004

Table 3: Mean values of the energy and particle asymmetry obtained for different models at particle level

Model	$< A_\phi >$ particle
No CR	-0.022 $\pm$ 0.004
SkII	-0.019 $\pm$ 0.004
SKI	0.000 $\pm$ 0.004
GH	0.044 $\pm$ 0.005

Table 4: Mean value of the angle asymmetry at particle level for different models

when there is a depletion in the particle density (less objects in the central region) or should decrease when there is an enhancement of the particle activity in the central region.

Starting from the particle flow the following quantity is computed for each event:

$$A_\phi = \frac{\psi_A+\psi_B-\psi_C-\psi_D}{\psi_A+\psi_B+\psi_C+\psi_D}$$

where ψ_{region} is the minimum angle between the region bisector and any particle i onto the projection plane: $\psi_{region} = min(|\phi^i_{rec} - 0.5|)$.

The asymmetry distributions are shown in figure 11 for the particle level for the same models as shown in the previous figures. The CR effects are seen effectively as an increase of the number of events with positive asymmetry (corresponding to relative particle enhancement in regions C and D). The mean values of the Monte Carlo distributions are summarised in table 4.

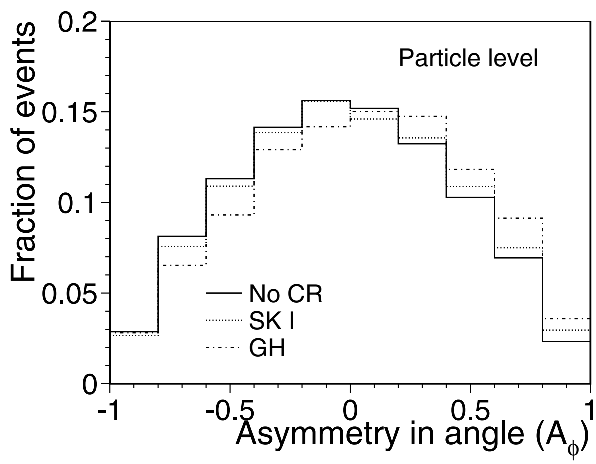

Figure 11: Distributions of the angle asymmetry at particle level for various models

Like for the other asymmetry variables $< A_\phi >$ has a better sensitivity than the quatities based on the ratio R. Extrapolating to a full LEP2 statistics, effects like the ones given by the models SKI and GH can be probed significantly.

6 Conclusions

Despite the fact that the actual statistical precision for a single experiment using only data recorded at 189 GeV is large to have a definite answer on the existence or not of colour reconnection effects in hadronic decays of W pairs, the method introduced in this paper should be seen as promising. The energy and particle flow distributions are interesting variables to study particle activity in interjet regions. However it is essential to define observables which are Monte Carlo independent like the ratio R of particle flows and the asymmetry variables introduced in this work. Also to increase the confidence in the method the results obtained from the 4-jet hadronic W^+W^- decays should be compared to the results from 4-jet events obtained by mixing semi-leptonic events (free of any cross-talk effects).

The selection has to be reoptimized to improve the efficiency. This selection is mainly based on the W boost and should be reestimated at each different e^+e^- centre-of-mass energy given by LEP.

Also this paper is not discussing systematic uncertainties which may arise from experimental procedure to build the flow distributions and from process modelling. Possible sources which should be carefully investigated for doing these measurements are for example:

- Bose-Einstein effects
- background subtraction
- definition of the flow objects

A good understanding of these systematics together with an increase of the statistics and some optimization of the selection should lead to sufficient discrimination power among the various CR models to see if the data agree or not with the standard Monte Carlo without colour reconnections and eventually to extract limits on cross talk probabilities.

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